

THE CAPTURE AND SEQUESTRATION OF POWER PLANT CO₂

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INTRODUCTION

Electrical utilities in the U.S. produce about 7% of the world's CO₂ emissions from energy use. Worldwide, about one-third of all CO₂ emissions from fossil-fuel energy sources comes from electric power plants. Since power plants have the highest density of CO₂ emissions in terms of mass per area per time, they provide an appropriate focus as a control target.

Assuming that the build-up of CO₂ in the atmosphere will have some adverse climatological and geohydrological affects, we can mitigate these effects by either counteracting the CO₂ emitted by the power plants or directly reducing the CO₂ emissions themselves (see Figure 1). In terms of counteracting power plant CO₂ emissions, natural fixation of biomass is the most serious contender. Some geoengineering options, such as fertilizing the ocean to increase CO₂ uptake from the atmosphere or dusting the upper atmosphere to reduce incident solar radiation, have also been suggested (National Academy of Sciences, *et al.*, 1991). In terms of direct reduction of power plant CO₂ emissions, improved efficiency is the most practical approach for the short-term, while switching to alternative energy sources (e.g., solar, wind, geothermal) or nuclear energy will probably be required for the long-term. However, power plants have traditionally dealt with adverse airborne emissions, such as NO_x and SO₂, through flue gas clean-up. In this paper, we will review the options for CO₂ reduction by flue gas clean-up followed by the use or disposal of the captured CO₂.

CO₂ CAPTURE

The idea of capturing CO₂ from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO₂, especially for use in enhanced oil recovery (EOR) operations. A very simplified flow diagram of a power plant is shown in Figure 2. A typical composition of the flue gas from a coal-fired power plant is 75% (by volume) N₂, 15% CO₂, 6% water, and 4% residual components (O₂, SO₂, NO_x). To be useful, capture processes should concentrate the CO₂ to over 90% by volume. Potential processes include:

- Water absorption systems
- Chemical solvent systems
- Physical solvent systems
- Molecular sieves
- Cryogenic fractionation
- Membrane diffusion

All of these processes have significant energy requirements, which reduce the plant's conversion efficiency or net power output, increasing the amount of CO₂ produced per net kWh_e of electricity generated. Therefore, in evaluating the cost of these processes, the amount of CO₂ emissions avoided (CO₂ emissions with capture compared to a no capture baseline) is more important than the total amount of CO₂ captured. For example, for a coal-fired power plant using a monoethanolamine (MEA) scrubbing process, it costs \$25 to capture a ton of CO₂, but due to the large energy losses resulting from the capture process itself, the cost per ton of CO₂ emissions avoided is \$62 on an equivalent power output basis.

Several commercial CO₂ recovery plants using MEA scrubbing have been built and operated in the U.S., with the North American Chemical Plant in Trona, CA being in operation the longest (since 1978). The Trona plant is based on Kerr-McGee technology, which is now licensed by ABB Lummus Crest (Barchas and Davis, 1992). An alternative process has been developed by Dow and is licensed by Fluor-Daniel (Sander and Mariz, 1992). Studies have shown that capture of power plant CO₂ by the MEA process will more than double the cost of electricity for reducing CO₂ emissions by 85% (Booras and Smelser, 1991; Herzog, *et al.*, 1991). Other capture techniques, such as membrane separation, cryogenic fractionation, or molecular sieves are even more expensive (see Table 1).

Because flue gas capture of CO₂ primarily requires separating N₂ and CO₂, the idea of separating the N₂ prior to combustion in the power plant has been investigated by Wolsky, *et al.* (1991). This is shown schematically in Figure 3. An air separation plant removes most of the nitrogen prior to combustion, while flue gas is recycled to moderate the temperature in the furnace. Water is easily removed by condensation either before or after the recycle, yielding a flue gas that contains over 95% by volume CO₂. Analysis shows that this process is somewhat more economical than the MEA process (Herzog, *et al.*, 1991).

The use of physical solvents, such as Selexol, in pressure-swing absorption processes are not competitive with the MEA process for atmospheric combustion because the cost of compressing the flue gas is prohibitive. However, for integrated gasification combined cycle (IGCC) plants that operate at elevated pressures, the use of a pressure swing absorption process is very efficient. CO₂ capture and disposal from an IGCC plant would only increase electricity costs in a range estimated from 30% (Hendriks, *et al.*, 1991) to 70% (Booras and Smelser, 1991).

CO₂ UTILIZATION AND DISPOSAL

Once the CO₂ is captured, concern shifts to disposal or sequestering. In the U.S., over 1.8 billion tons of CO₂ is produced each year from power plants. One option is to use the CO₂. However, the amount of CO₂ used annually in the U.S. is only 1-2% of the total amount produced by power plants, and much of the current supply of CO₂ comes from very inexpensive sources - natural formations or chemical by-products (e.g., from an ammonia process). Therefore, for utilization to be a significant sink of CO₂, new uses need to be identified. Also, many of the uses proposed for CO₂ only delay its eventual release to the atmosphere for a very short time.

One proposal that would satisfy the key criteria of reducing atmospheric emissions of CO_2 and of being able to process large quantities of CO_2 is to transform the CO_2 to a fuel, such as methanol. By producing a fuel, our need for "virgin" fuels would be reduced, thereby reducing our total CO_2 emissions. However, carbon in the form of carbon dioxide is in a low energy state and would require significant amounts of energy to be transformed to a high energy fuel. Two types of processes have been proposed to supply this energy, "light" processes utilizing photosynthetic pathways and "dark" processes utilizing chemical reformation (Aresta, *et al.*, 1992). The source of energy proposed in the *dark* processes is frequently hydrogen (H_2). However, if large amounts of inexpensive H_2 are available, it would be more efficient to burn them directly in a power plant and displace fossil fuel use rather than to try to reprocess the CO_2 . The *light* processes use solar energy as a power source. For example, large microalgae ponds would be located near a power plant and the captured CO_2 would be distributed through the ponds. The microalgae would be routinely harvested, processed, and used as a fuel. While this scheme has many barriers (large land requirements, limited geographical applicability etc.), it is still the most promising large-scale utilization option currently available.

For CO_2 disposal, there are four primary candidates: oil reservoirs, gas reservoirs, aquifers, and the deep ocean. CO_2 is currently injected in oil reservoirs for EOR and, therefore, may also be considered utilization of CO_2 . However, current EOR practices also inject water, which is not consistent with maximizing CO_2 sequestering. Also, the capacity of oil reservoirs is limited and they are not ubiquitously located. Depleted gas reservoirs have a somewhat larger capacity, but using CO_2 to enhance gas recovery is not a practical technique. Frequently, depleted gas wells have been cemented closed as required by law, so using them for CO_2 disposal requires reopening old wells or drilling new wells. The final land base disposal option is in aquifers, which are widely available. However, there is a great lack of geotechnical data on the behavior of pressurized CO_2 in such reservoirs. Some simulations suggest that flow processes would be dominated by viscous fingering and gravity segregation, resulting in a sweep efficiency of only 1-5% (van der Meer, 1992). Also, the integrity of aquifers as a long-term CO_2 storage system may be risky. Since CO_2 , unlike natural gas, is heavier than air, a large release displaces oxygen and may cause death by suffocation. A relevant example occurred in 1986 in Cameroon, where naturally trapped CO_2 was released in large quantities from Lake Nyasa resulting in 1,200 deaths.

The deep ocean has the advantage of being an almost limitless repository for CO_2 . However, the residence time of CO_2 sequestered in the deep ocean is finite, depending on the depth of injection; estimates range from 50 years at 500 m to 1000 years at 3000 m (Liro, *et al.*, 1992). Of course, the deeper the injection, the more the cost. While environmental concerns have been raised about ocean disposal of CO_2 , impacts will probably be very localized. Transport and injection of CO_2 into the ocean, while expensive, is technologically feasible today. If CO_2 is injected below 500 m, the possibility of hydrate formation exists. Research into the kinetics of hydrate formation and how to use hydrates to increase sequester time and/or reduce costs is needed.

STATUS OF CURRENT RESEARCH

Research on global climate change can be divided into science, engineering, and policy. While the U.S. is the leader in global change science research, spending about

\$1 billion per year, Japan in the leader in engineering research directed at mitigation. In FY91, the Japanese government's research budget just for CO₂ capture and fixation technology was about \$22 million. In addition, research is also being funded by Japanese industry and utilities. The Japanese research on CO₂ capture is spread over most of the topics discussed in this paper, with a special emphasis on deep ocean disposal (Shindo, *et al.*, 1992).

In addition to Japan, both Norway and The Netherlands have very aggressive research programs. The Netherlands have focused on capture from IGCC plants, with storage in depleted gas wells. Their research agenda also includes studying membrane separation, the use of fuel cells, and storage in aquifers. The Norwegians' research projects include looking for improved chemicals for CO₂-removal from exhaust gas, new and improved gas turbines, EOR research, studying CO₂-hydrates, and funding system studies. Much of this research is being carried out through Statoil, the national oil company. Statoil is currently considering a project to inject a million tonnes/year of CO₂ into an offshore aquifer (Kaarstad, 1992).

An international effort (including the U.S.) under the auspices of the International Energy Agency (IEA) is underway, with British Coal as the operating agent. The goal of the IEA effort is to evaluate "technology options for the control of greenhouse gas emissions from fossil fuel utilisation." They will identify and conduct research into the most promising capture and disposal options (Jack, *et al.*, 1992). The U.S. Department of Energy's Office of Coal Technology budgeted \$150,000 this fiscal year, focused mainly on biological utilization of CO₂. Next year's estimated budget is \$900,000 for projects yet to be specified. In Canada, a project is underway in Alberta on using CO₂ for EOR and maximizing the storage potential of oil reservoirs (Bailey, 1992). In Germany, an IGCC demonstration plant with CO₂ capture using Purisol (a physical sorbent) is under construction for start-up in 1995 (Schütz, *et al.*, 1992). The above list is not complete, but gives a flavor of the activity currently on-going for CO₂ capture and disposal research.

CONCLUSIONS

While the capture of CO₂ from power plant flue gas may be energy intensive and expensive, it is technically feasible. Several flue gas CO₂ capture plants are currently in operation, producing CO₂ for industrial uses. While further research on CO₂ capture processes may reduce costs or lower energy requirements, the major research challenge is to find methods of sequestering or utilizing the captured CO₂ that are technically feasible, economically viable, and environmentally sustainable.

FURTHER DOCUMENTATION

For a more detailed analysis of the issues outlined in this paper, we refer the reader to the proceedings of the *First International Conference on Carbon Dioxide Removal*. The proceedings are scheduled for publication in the June issue of *Energy Conversion and Management* (Pergamon Press). Also, our report to the U.S. Department of Energy on *A Research Needs Assessment for the Capture, Utilization, and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants* should be available in the fall of 1992.

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Table 1
Comparison of CO₂ Capture Technologies

Process	Energy Penalty (%)	Nominal CO ₂ Recovery (%)	Net Reduction of CO ₂ Emissions (% of Base Case)	Relative Cost of Electricity
Base Case -- No CO ₂ Removal	0	0	0	1.0
IGCC ^a	13	88	86.2	1.3
IGCC ^b	20	90	87.5	1.7
Air Separation FG Recycling ^c	25	100	100	1.9
Amine Scrubbing with Congenerated Steam ^b	35	90	84.6	2.6
Molecular Sieves ^d	80	90	50	5.1
Cryogenic Fractionation ^c	75	90	60	---
Membrane Separation ^c	63	80	46	---

Sources:

^aHendriks, *et al.* (1991)

^bBooras and Smelser (1991)

^cHerzog, *et al.* (1991)

^dFulkerson, *et al.* (1990)

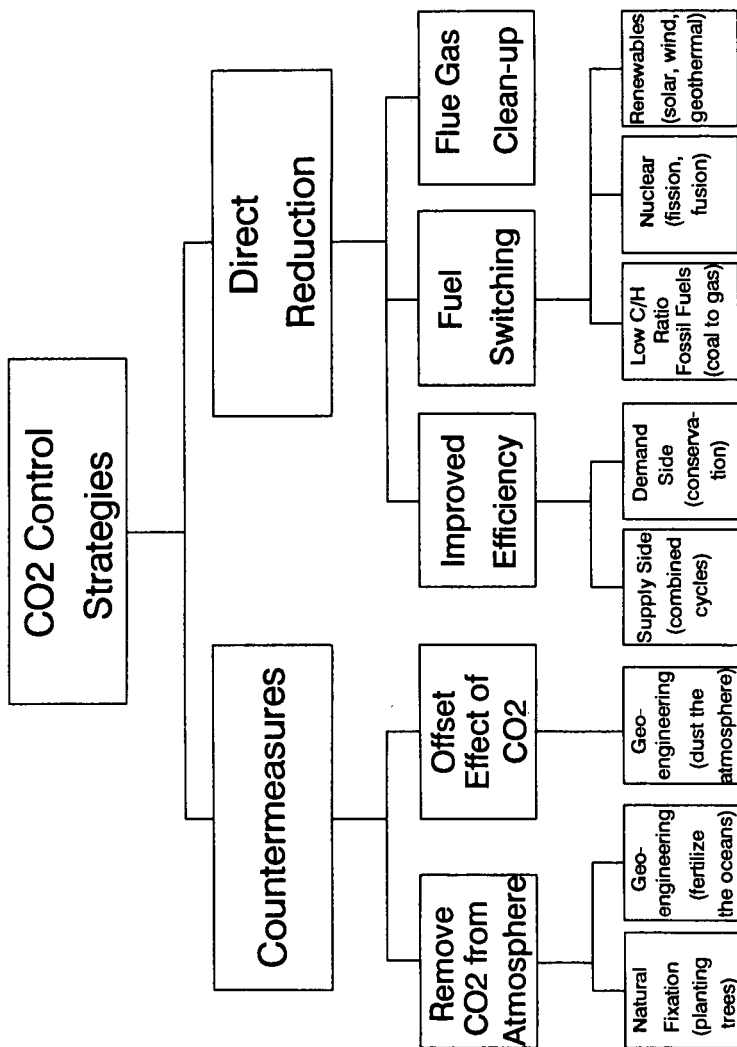


Figure 1: CO₂ Control Strategy Options.

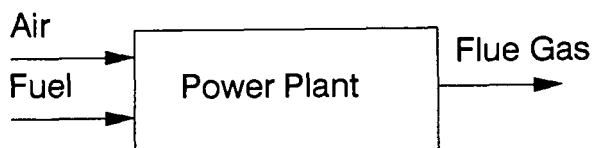


Figure 2: Power Plant Schematic.

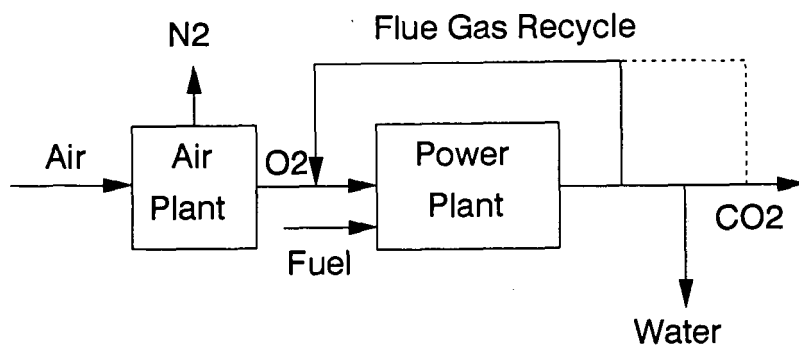


Figure 3: Air Separation/Flue Gas Recycle Power Plant Schematic.